Manchester, EPS 2007

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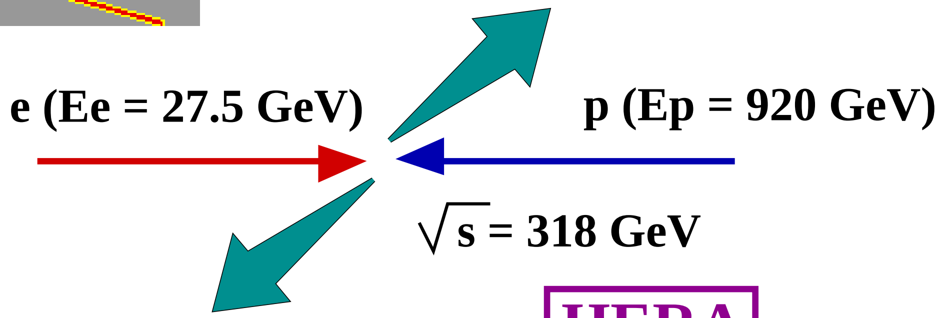
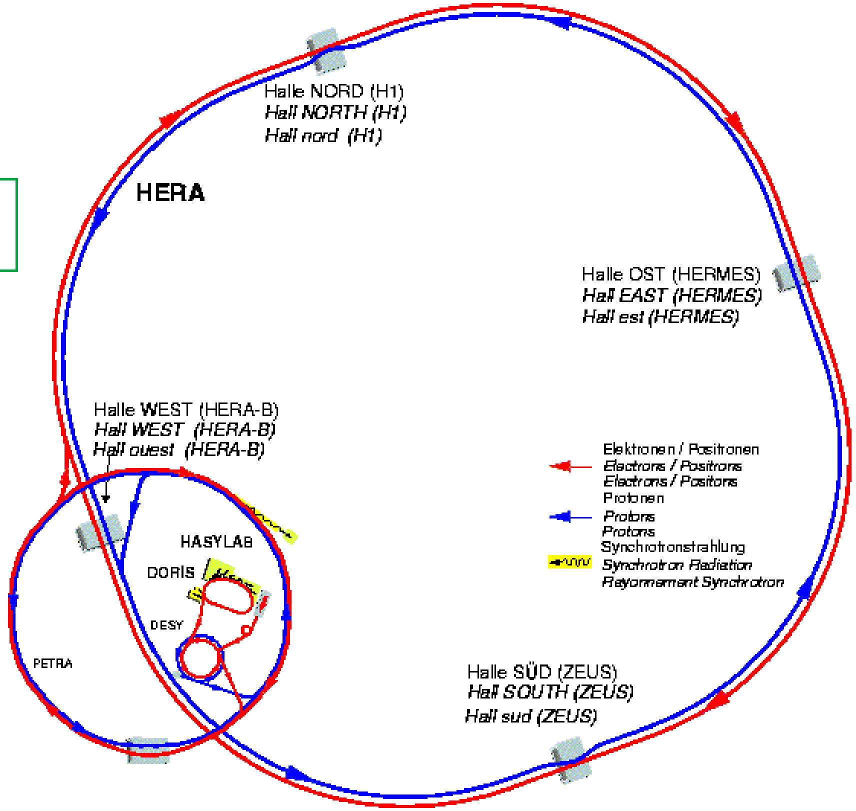
Substructure of jets in NC DIS

Juan Terrón (Universidad Autónoma de Madrid, Spain)

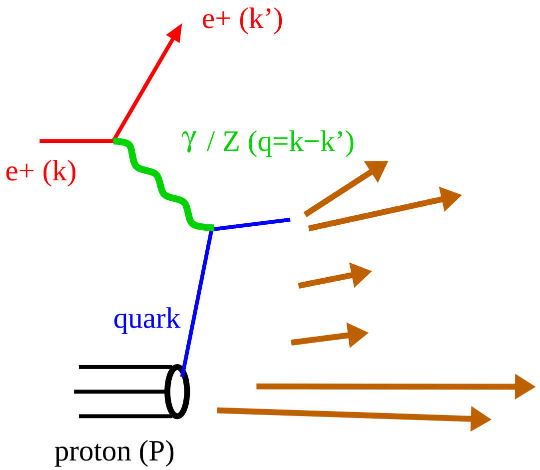
ZEUS Collaboration



HERA



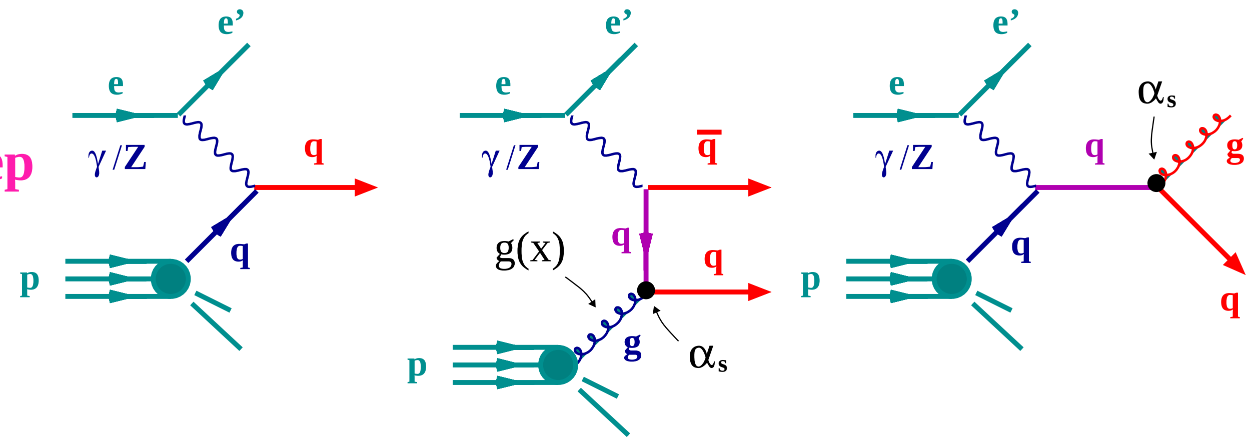
Neutral Current Deep Inelastic Scattering



For a given ep centre-of-mass energy, $\sqrt{s}$, the fully inclusive cross section for $ep \rightarrow e + X$ can be described by two independent kinematic variables, e.g.

$$Q^2 = -(k - k')^2 \text{ and } x_{Bj} = Q^2/(2P \cdot q)$$

Jet production in neutral current deep inelastic scattering up to $\mathcal{O}(\alpha_s) \rightarrow$



Quark-Parton Model | Boson-Gluon Fusion | QCD Compton

Measurements of jet cross sections in NC DIS at high Q^2 have allowed precise tests of the pQCD calculations

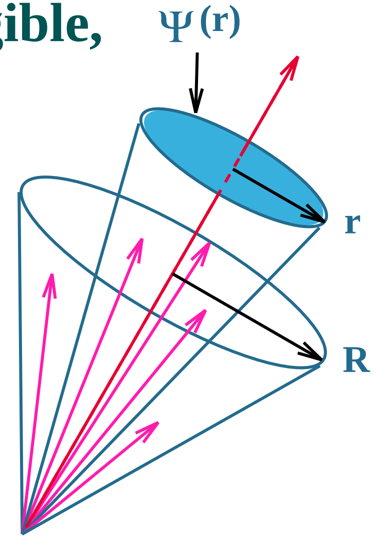
$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx \, f_a(x, \mu_F^2) \, d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R^2, \mu_F^2)$$

as well as precise determinations of α_s

NOW: Let's test pQCD to the extreme... $\rightarrow$

Jet Substructure in Neutral Current Deep Inelastic Scattering

- At sufficiently high E_T^{jet}, where fragmentation effects become negligible, the jet substructure is expected to be calculable by pQCD



- Measurements of jet substructure allow investigations on

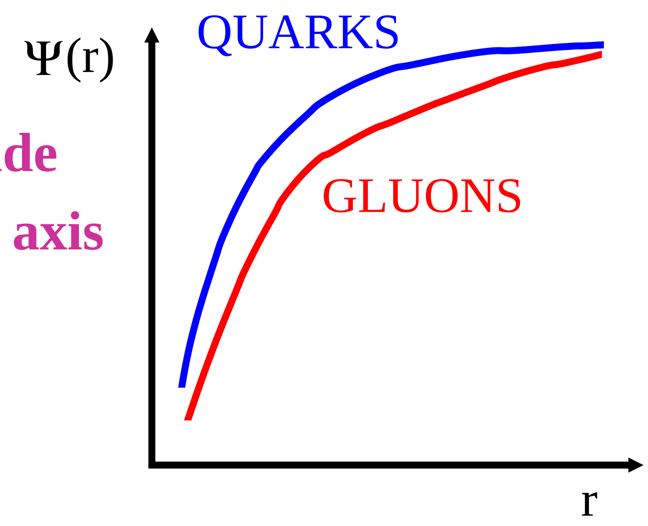
$\longrightarrow$ the differences between quark- and gluon-initiated jets and

$\longrightarrow$ the dynamics of the different partonic final states,

$\longrightarrow$ as well as determinations of α_s

- **Integrated jet shape:** $$\langle\Psi(r)\rangle = \frac{1}{N_{jets}} \sum_{jets} \frac{E_T(r)}{E_T^{jet}}$$

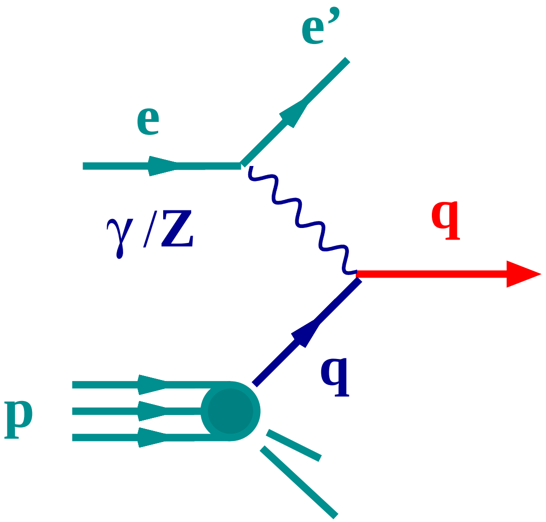
Average fraction of the jet's transverse energy that lies inside a circle in the η-ϕ plane of radius r concentric with the jet axis



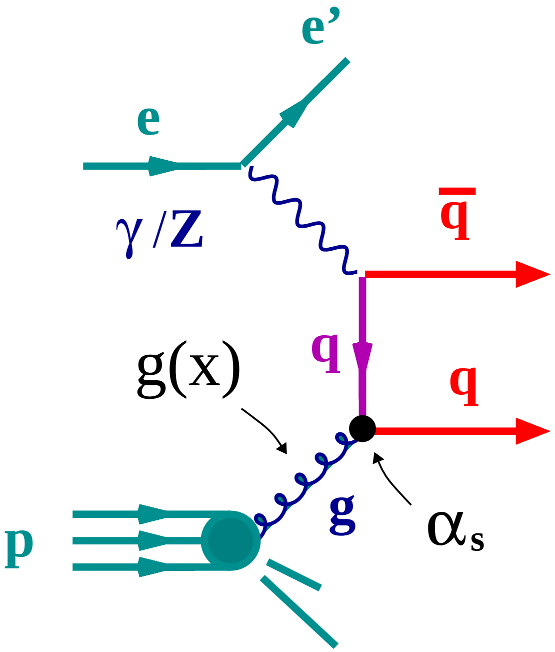
- QCD predicts that gluon jets are broader than quark jets

$\Rightarrow \Psi_{QUARKS}(r) > \Psi_{GLUONS}(r)$

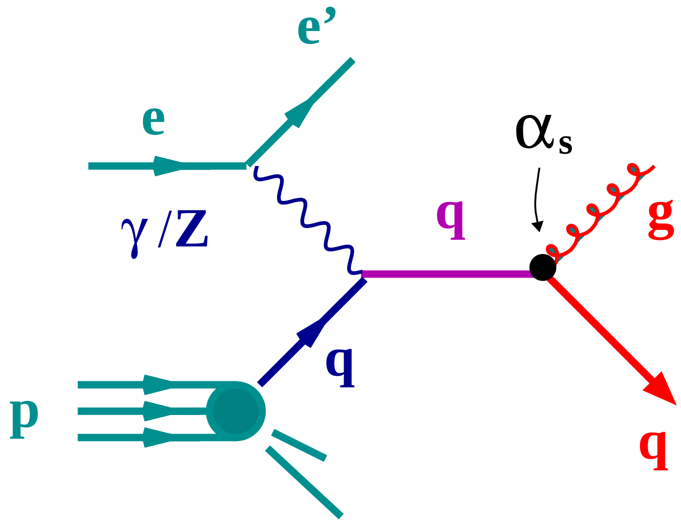
Jet Substructure in Neutral Current Deep Inelastic Scattering



Quark-Parton Model



Boson-Gluon Fusion



QCD Compton

One-jet events

Enriched in quark jets

Two-jet events

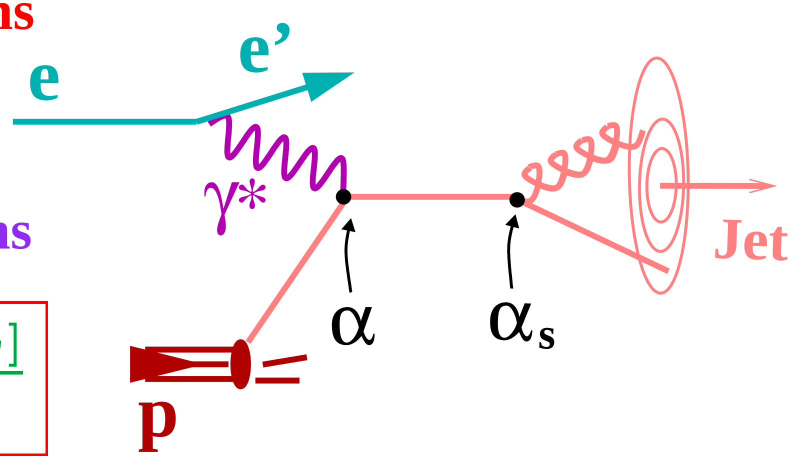
Higher content of gluon jets

Jet Substructure in Neutral Current Deep Inelastic Scattering

- **Comparison with calculations:**

→ **Monte Carlo generators (ARIADNE-CDM, LEPTO-MEPS) approximate the substructure of jets with parton showers**

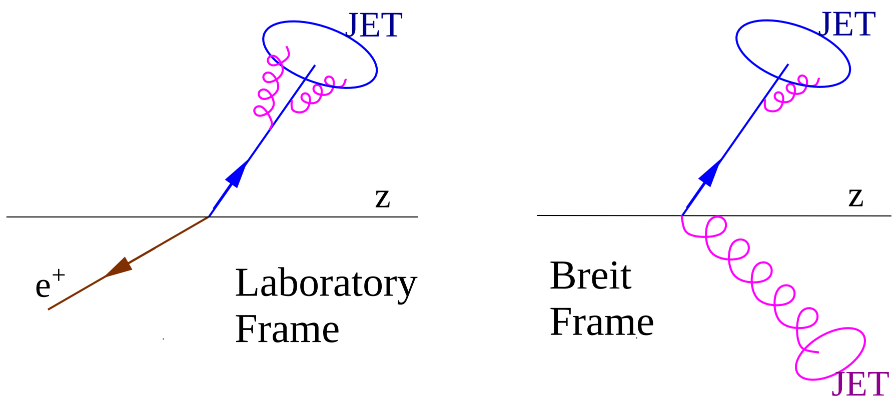
→ **Fixed-order QCD calculations: at lowest order a jet consists of one parton (no structure); higher-order terms give the non-trivial contributions**



- **E.g. the lowest non-trivial-order contribution for one-jet events is given by $\mathcal{O}(\alpha\alpha_s)$ pQCD calculations**

$$\langle 1-\Psi(r)\rangle = \frac{\int dE_T\ E_T\,[d\sigma(ep\rightarrow 2\text{partons})/dE_T]}{E_T^{jet}\ \sigma_{\rm jet}(E_T^{jet})}$$

- **NLO QCD calculations of jet substructure can be made in the laboratory frame since it is possible to have 3 partons in the same jet (not possible in the Breit frame)**

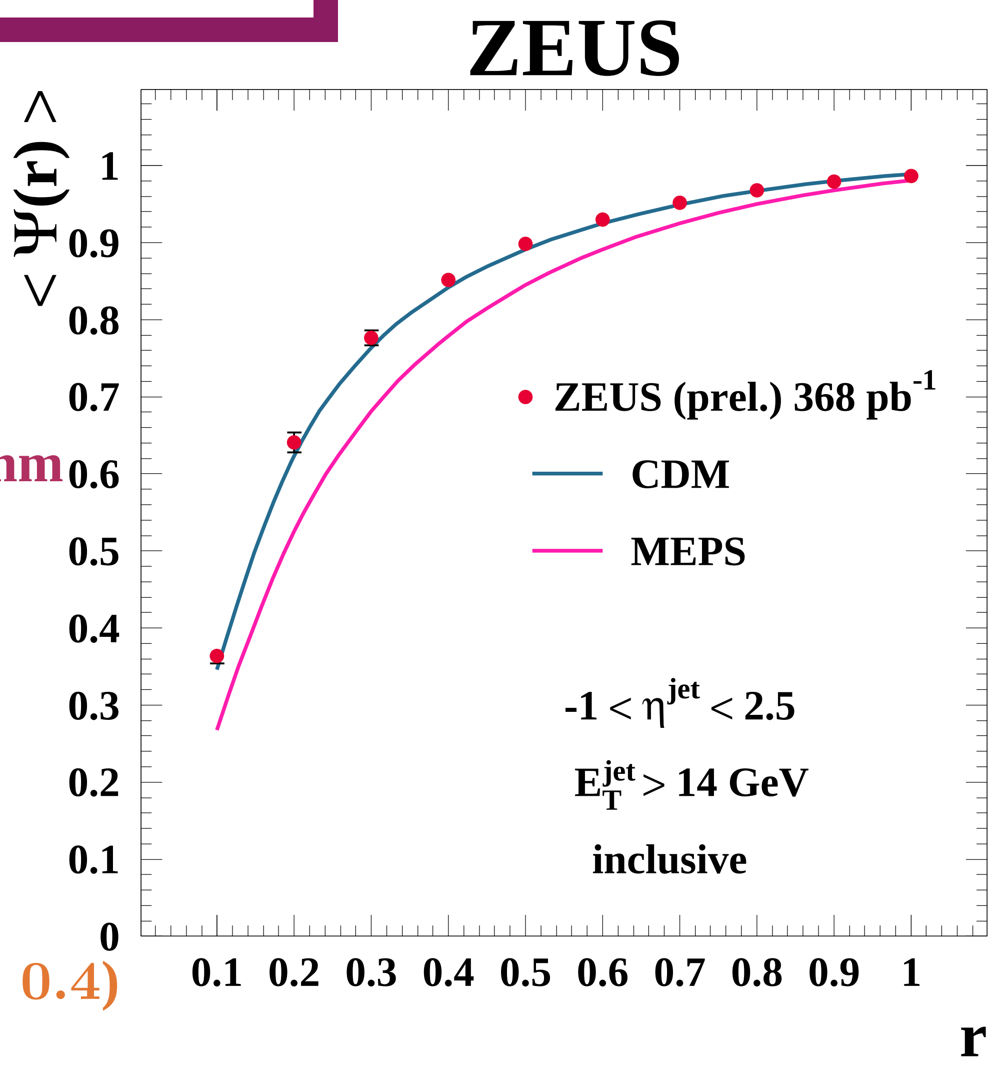


Measurements of Jet Substructure in NC DIS

- Measurement of $\langle\Psi(r)\rangle$ for an inclusive sample of jets in NC DIS with
$$Q^2 > 125 \text{ GeV}^2$$
using HERA II data: $\mathcal{L} = 368 \text{ pb}^{-1}$

- Jets are defined using the k_T-cluster algorithm (longitudinally invariant mode) in the laboratory frame and required to have
$$E_T^{jet}(\text{Lab}) > 14 \text{ GeV}$$
$$-1 < \eta^{jet}(\text{Lab}) < 2.5$$

- The measurements of $\langle\Psi(r)\rangle$ have been corrected for detector effects ($< 10\%$ for $r \geq 0.4$)



- Comparison to QCD-inspired Monte models:

$\rightarrow$ the colour-dipole model (CDM, ARIADNE) reproduces the data well

$\rightarrow$ matrix-elements plus parton-showers (MEPS, LEPTO) predict too-broad jets

Measurements of Jet Substructure in NC DIS

- Measurement of $\langle\Psi(r)\rangle$ in NC DIS with $Q^2 > 125$ GeV^2 using $\mathcal{L} = 368$ pb^{-1} for two samples of jets:

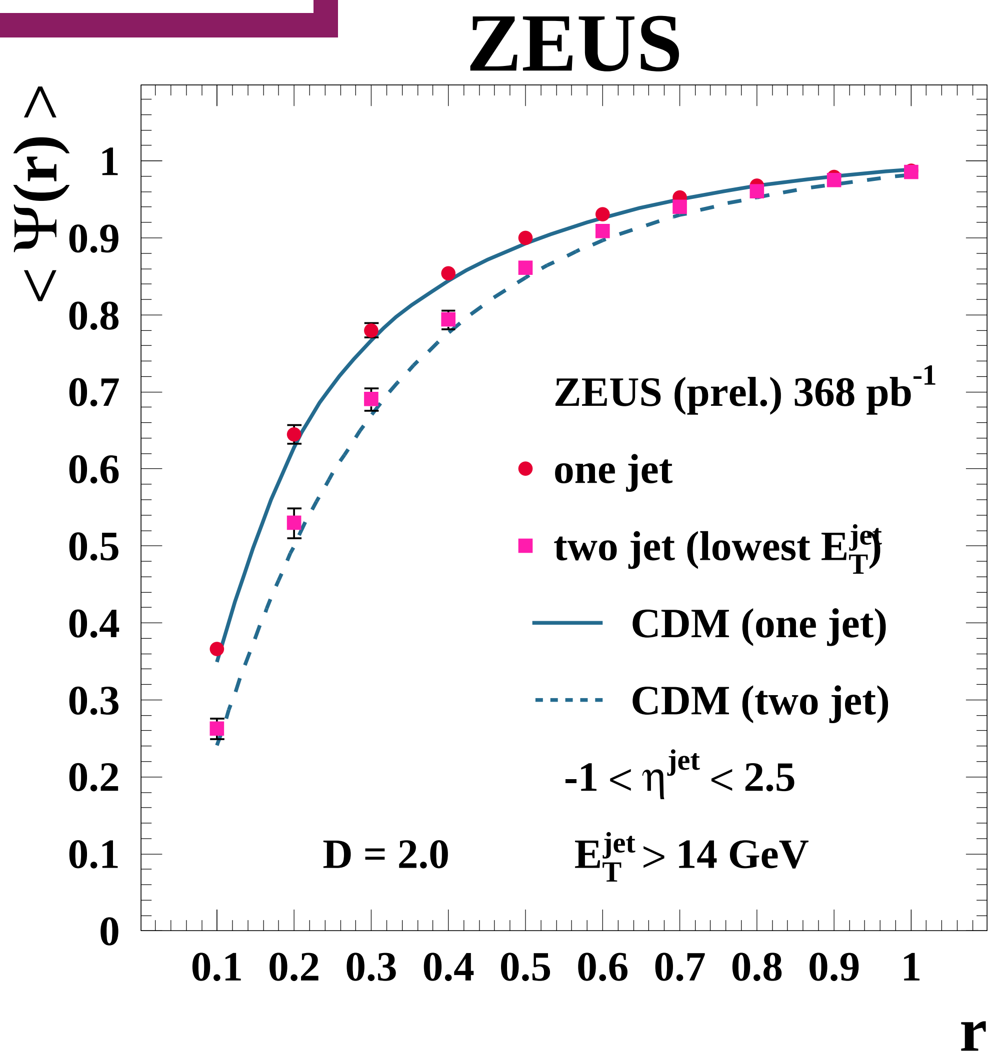
One-jet events

$E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$

Two-jet events

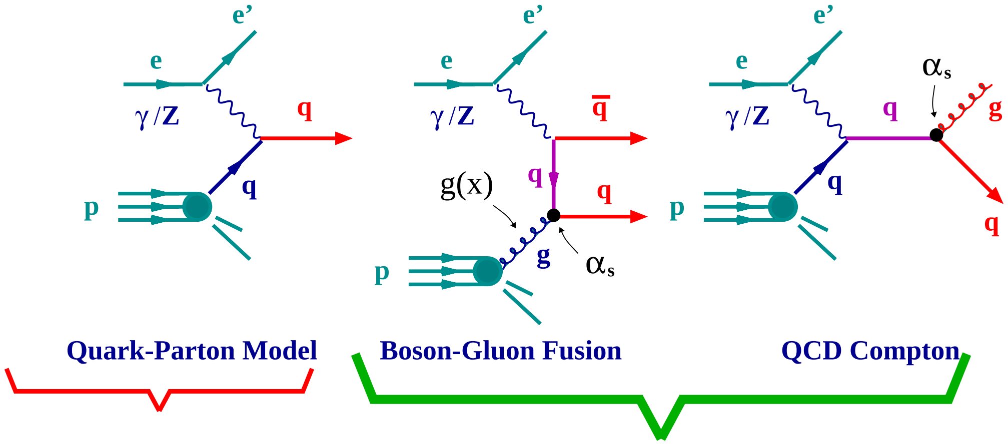
both jets are required to have
$E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$
and to be close to each other in the η-ϕ plane
distance jet-jet$= \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2$

$\longrightarrow$ the jet with lowest E_T^{jet} is considered



- The lowest-E_T^{jet} jet in the two-jet event sample is BROADER

Measurements of Jet Substructure in NC DIS

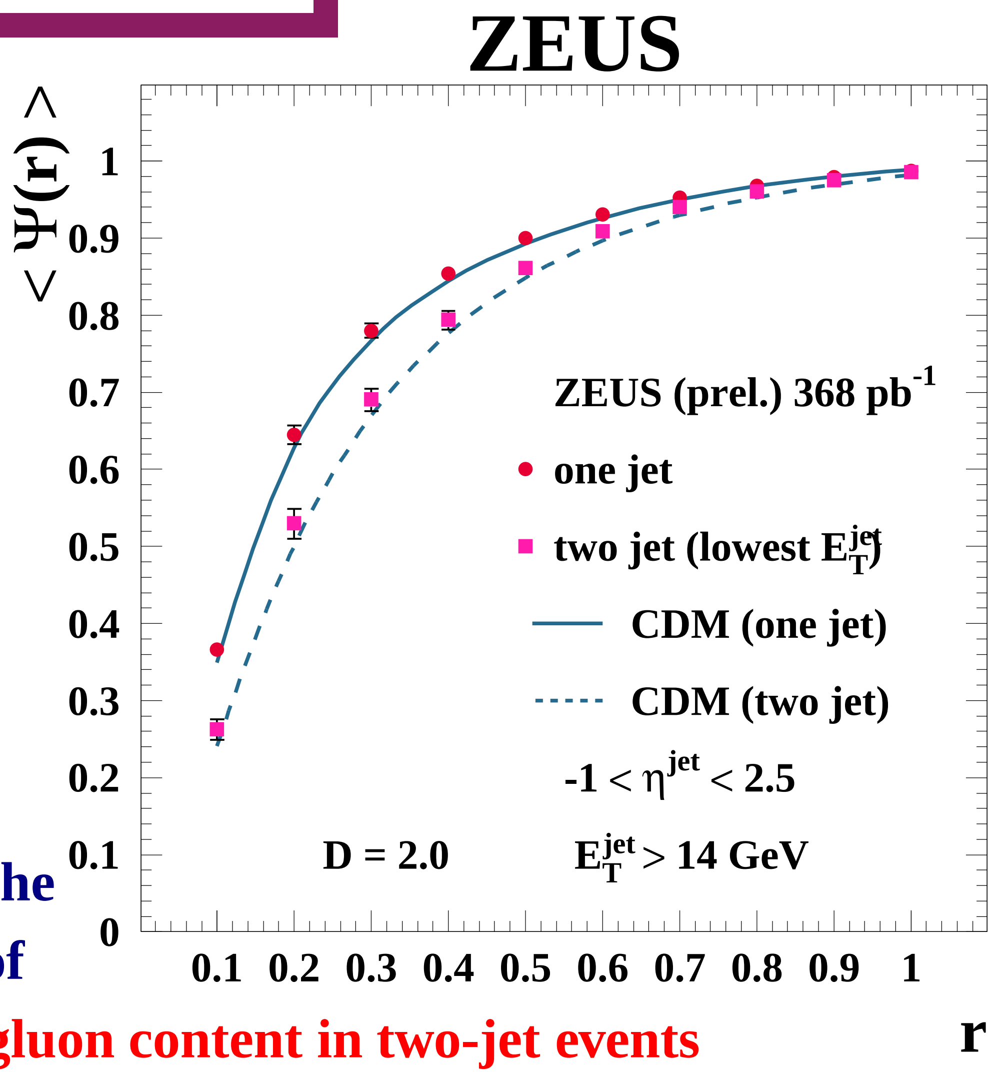


One-jet events

- Enriched in quark jets

Two-jet events

- Higher content of gluon jets



- The observation that the lowest-E_T^{jet} jet in the two-jet event sample is BROADER than that of the one-jet sample is consistent with a higher gluon content in two-jet events

→ The colour-dipole model (CDM, ARIADNE) reproduces the data reasonably well; in particular, the difference in jet shape between the two samples

Measurements of Jet Substructure in NC DIS: $14 < E_T^{jet} < 17$ GeV

- Measurement of $\langle \Psi(r) \rangle$ in NC DIS with $Q^2 > 125$ GeV^2 using $\mathcal{L} = 368$ pb^{-1} for two samples of jets:

One-jet events

$14 < E_T^{jet} < 17$ GeV, $-1 < \eta^{jet} < 2.5$

Two-jet events

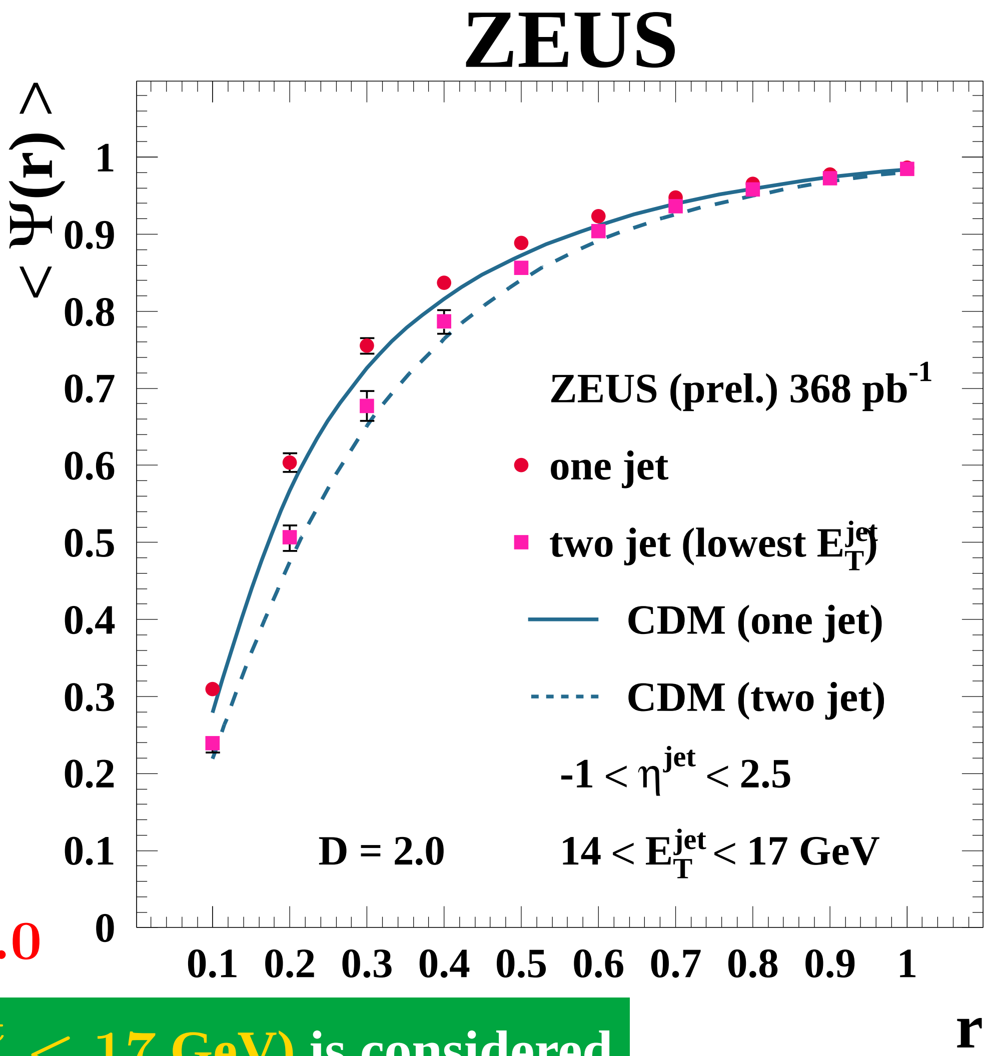
both jets are required to have

$E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$

and to be close to each other in the η-ϕ plane

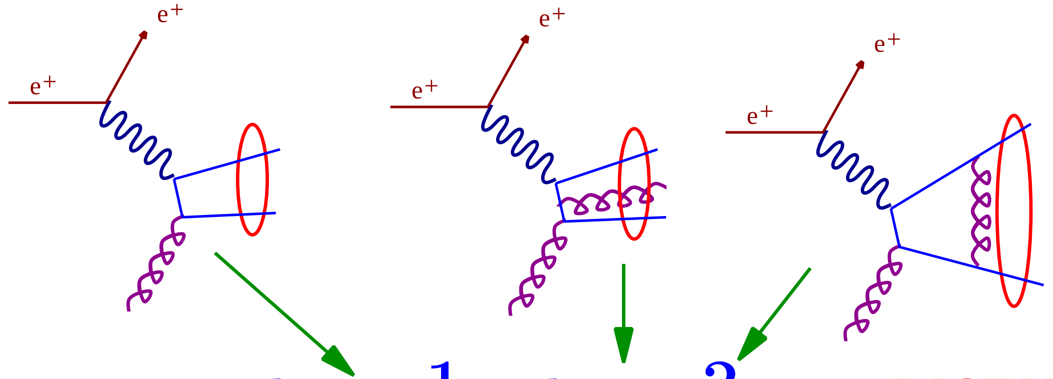
distance jet-jet$= \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2.0$

$\longrightarrow$ the jet with lowest E_T^{jet} (and $14 < E_T^{jet} < 17$ GeV) is considered



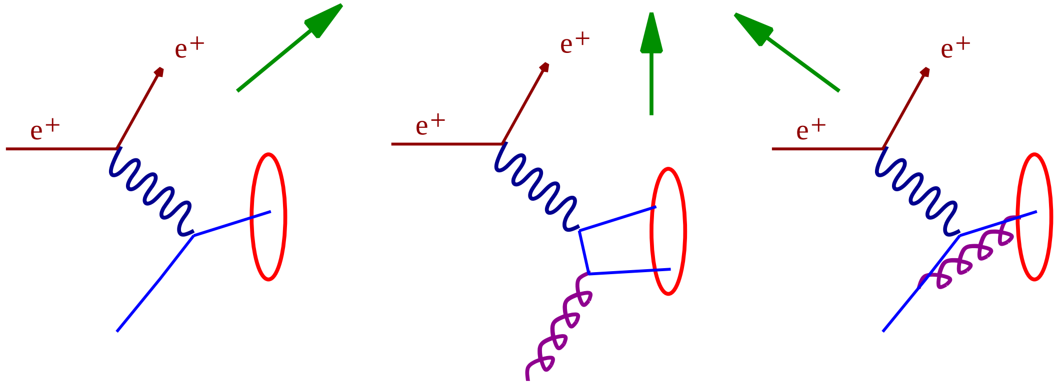
- The lowest-E_T^{jet} jet in the two-jet event sample is BROADER

NLO QCD calculations for inclusive/one-jet production



$$\langle 1 - \Psi(r) \rangle = \frac{b_1 \cdot \alpha_s^1 + b_2 \cdot \alpha_s^2}{a_0 \cdot \alpha_s^0 + a_1 \cdot \alpha_s^1}$$

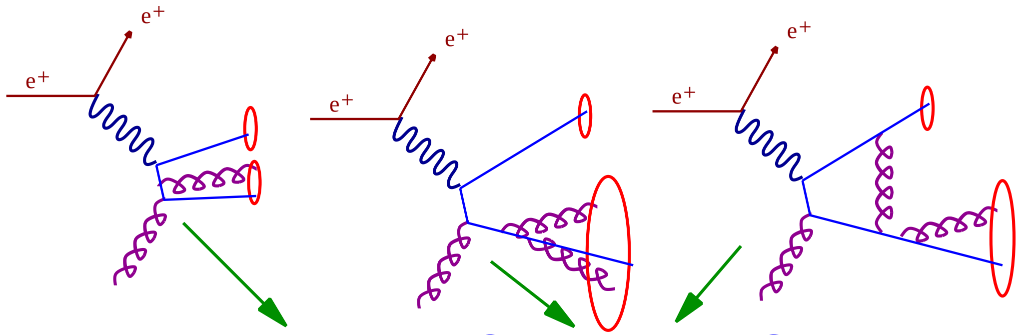
DISENT program
S. Catani and M.H. Seymour
Nucl. Phys. B485 (1997) 291



- **DISENT program:** $\alpha_s(M_Z) = 0.118$; $\mu_R = \mu_F = Q$; CTEQ6 proton PDFs

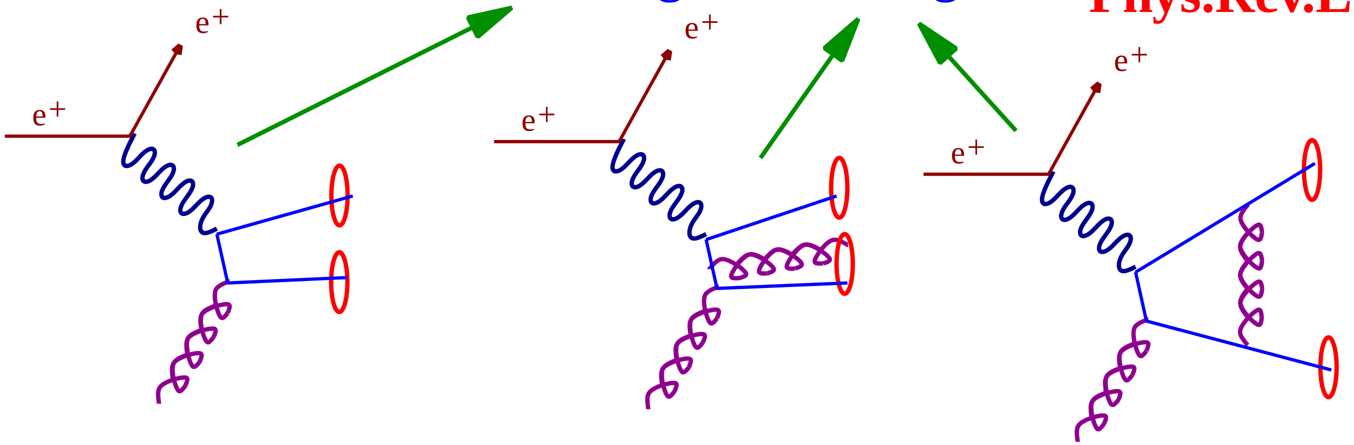
$\rightarrow$ Dominant theoretical uncertainty: terms beyond NLO, $< 5\%$ for $r \geq 0.2$

NLO QCD calculations for two-jet production



$$\langle 1 - \Psi(r) \rangle = \frac{d_2 \cdot \alpha_s^2 + d_3 \cdot \alpha_s^3}{c_1 \cdot \alpha_s^1 + c_2 \cdot \alpha_s^2}$$

NLOJET++ program
Z. Nagy and Z. Trocsanyi
Phys.Rev.Lett. 87 (2001) 082001



- **NLOJET++ program:** $\alpha_s(M_Z) = 0.118$; $\mu_R = \mu_F = Q$; **CTEQ6 proton PDFs**

Measurements of Jet Substructure in NC DIS vs NLO QCD

- Measurement of $\langle \Psi(r) \rangle$ in NC DIS with $Q^2 > 125$ GeV^2 using $\mathcal{L} = 368$ pb^{-1} for two samples of jets:

One-jet events

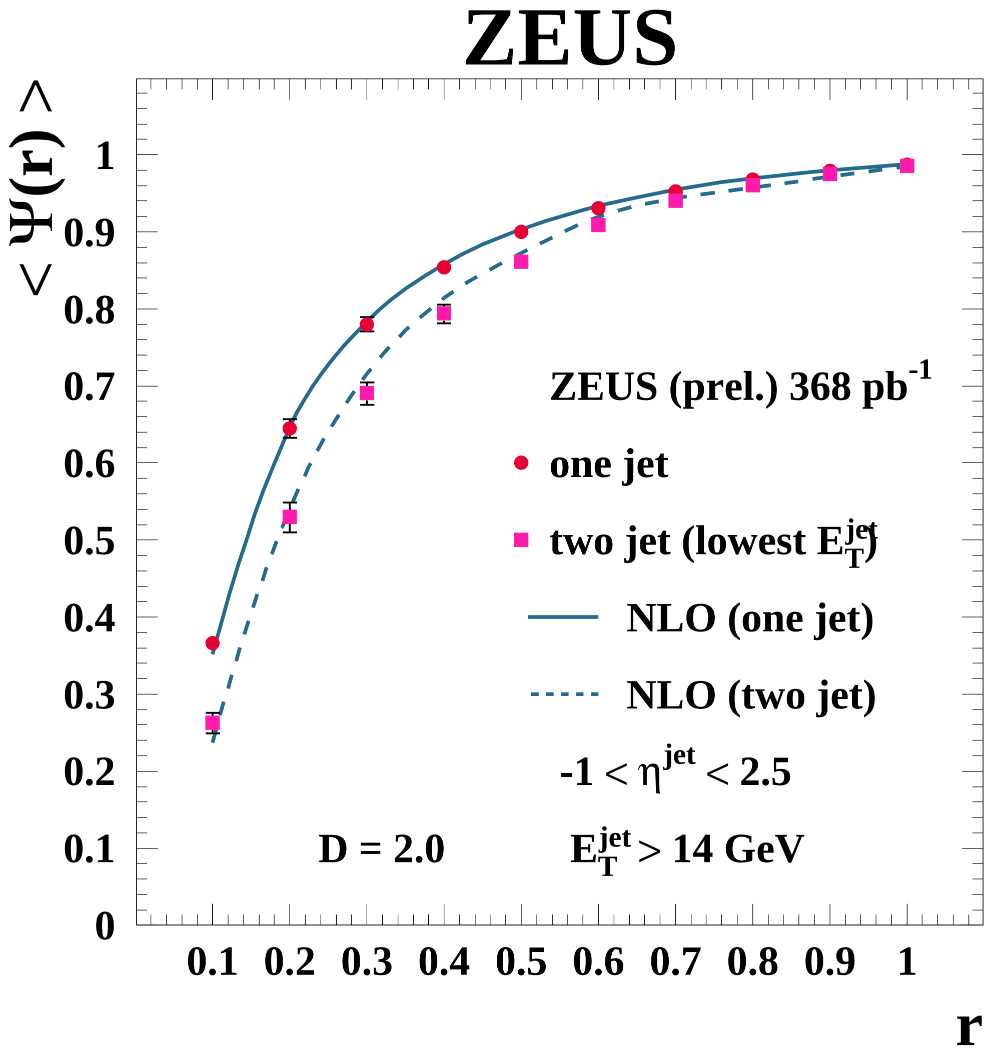
$E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$

Two-jet events

$E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$

distance jet-jet$= \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2$

$\longrightarrow$ the jet with lowest E_T^{jet} is considered



NLO QCD calculations corrected for hadronisation effects ($< 10\%$ for $r \geq 0.4$) reproduce the data reasonably well; in particular, the difference in jet shape between the two samples

Measurements of Jet Substructure in NC DIS vs NLO QCD

- Measurement of $\langle\Psi(r)\rangle$ in NC DIS with $Q^2 > 125$ GeV^2 using $\mathcal{L} = 368$ pb^{-1} for two samples of jets:

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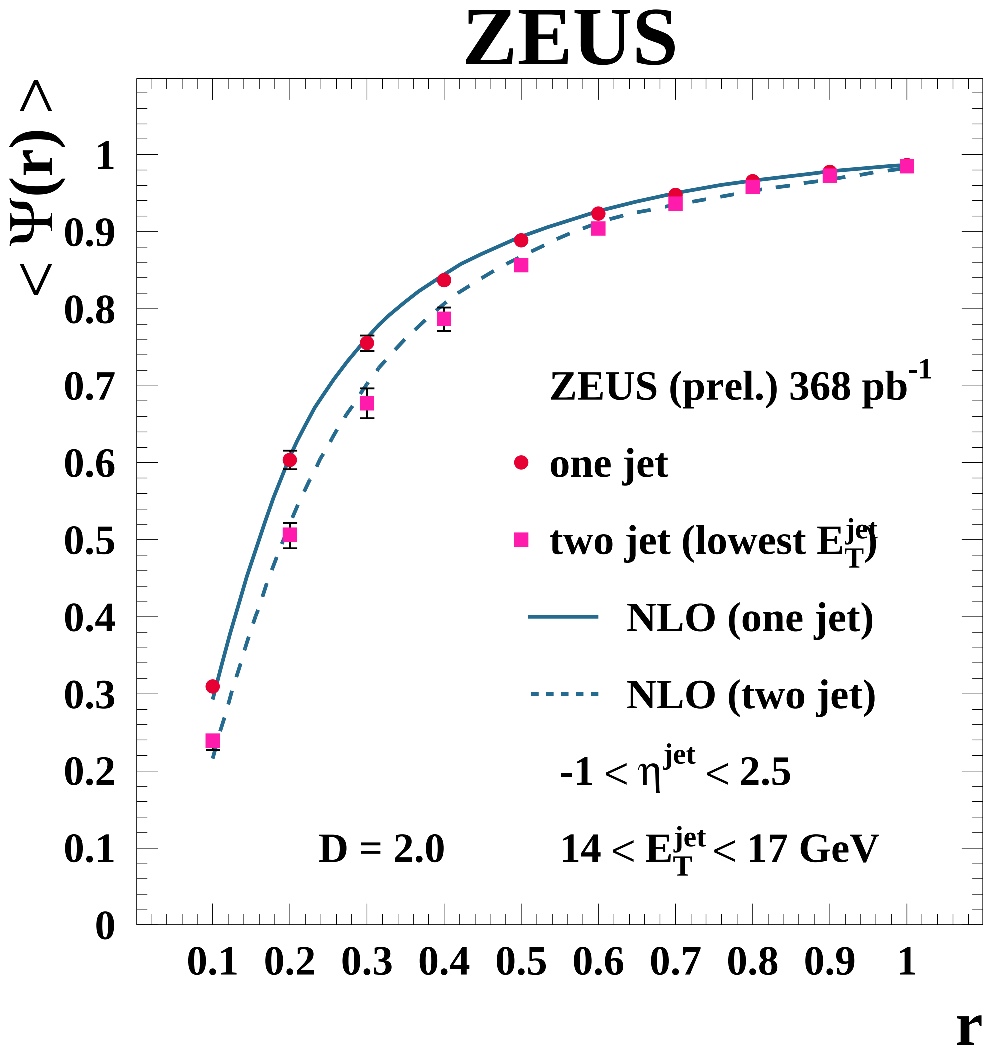
$\longrightarrow$ the jet with lowest E_T^{jet} (and $14 < E_T^{jet} < 17$ GeV) is considered



NLO QCD calculations corrected for hadronisation effects ($< 10\%$ for $r \geq 0.4$) reproduce the data reasonably well; in particular, the difference in jet shape between the two samples

Jet Substructure in NC DIS: subjets

- The internal structure of jets has also been studied using the subjet topology

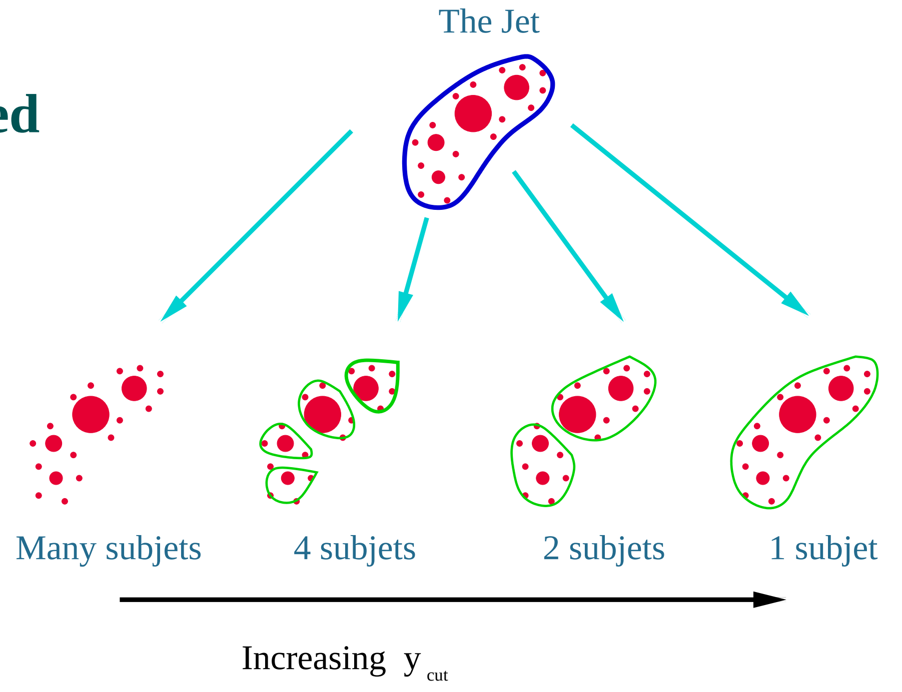
- Subjets are resolved within a jet by reapplying the k_T-cluster algorithm on all the particles belonging to the jet until for every pair of particles the distance betwen clusters is above

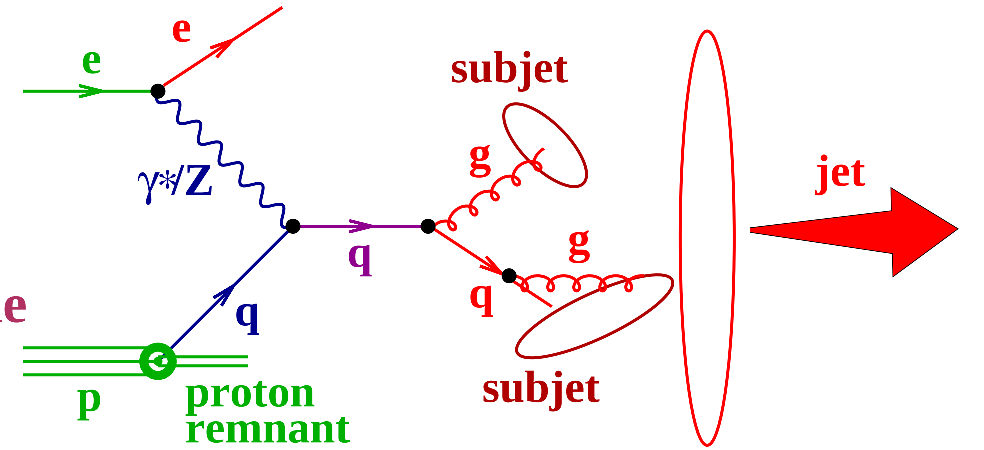
$$d_{cut} = y_{cut} \cdot (E_T^{jet})^2$$

→ all remaining clusters are called subjets

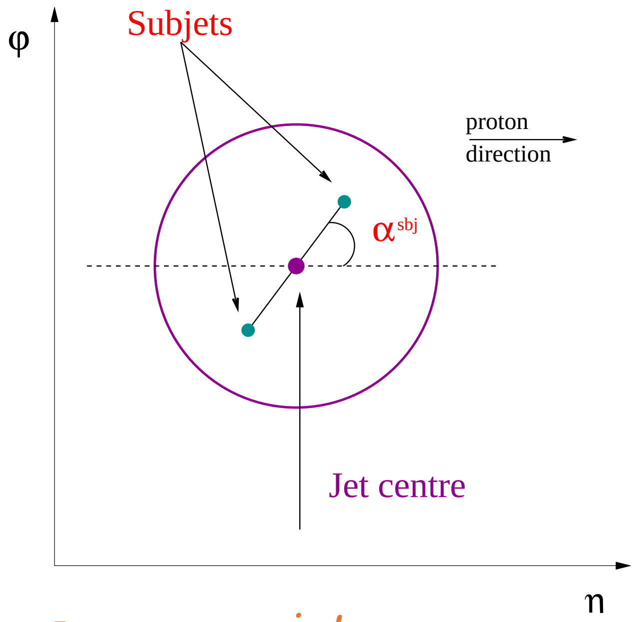
→ the subjet multiplicity depends upon the resolution parameter y_{cut}

- The distributions of subjets are sensitive to the pattern of parton radiation





Measurements of Subjet Distributions in NC DIS



- The pattern of QCD radiation from a primary parton has been studied by measuring normalised cross sections as functions of subjet variables
  E_T^{sbj}/E_T^{jet}, $\eta^{sbj} - \eta^{jet}$, $\phi^{sbj} - \phi^{jet}$ and α^{sbj}

- Measurements of the normalised cross sections were done in NC DIS for $Q^2 > 125$ GeV^2:

$\longrightarrow$ Jets are defined using the k_T-cluster algorithm in the laboratory frame; at least one jet with $E_T^{jet} > 14$ GeV and $-1 < \eta^{jet} < 2.5$

$\longrightarrow$ Selected sample of jets: jets with exactly TWO subjets at $y_{cut} = 0.05$

- Comparison to LO ($\mathcal{O}(\alpha_s)$) and NLO ($\mathcal{O}(\alpha_s^2)$) QCD calculations using DISENT:

$\longrightarrow$ MRST99 set of proton PDFs

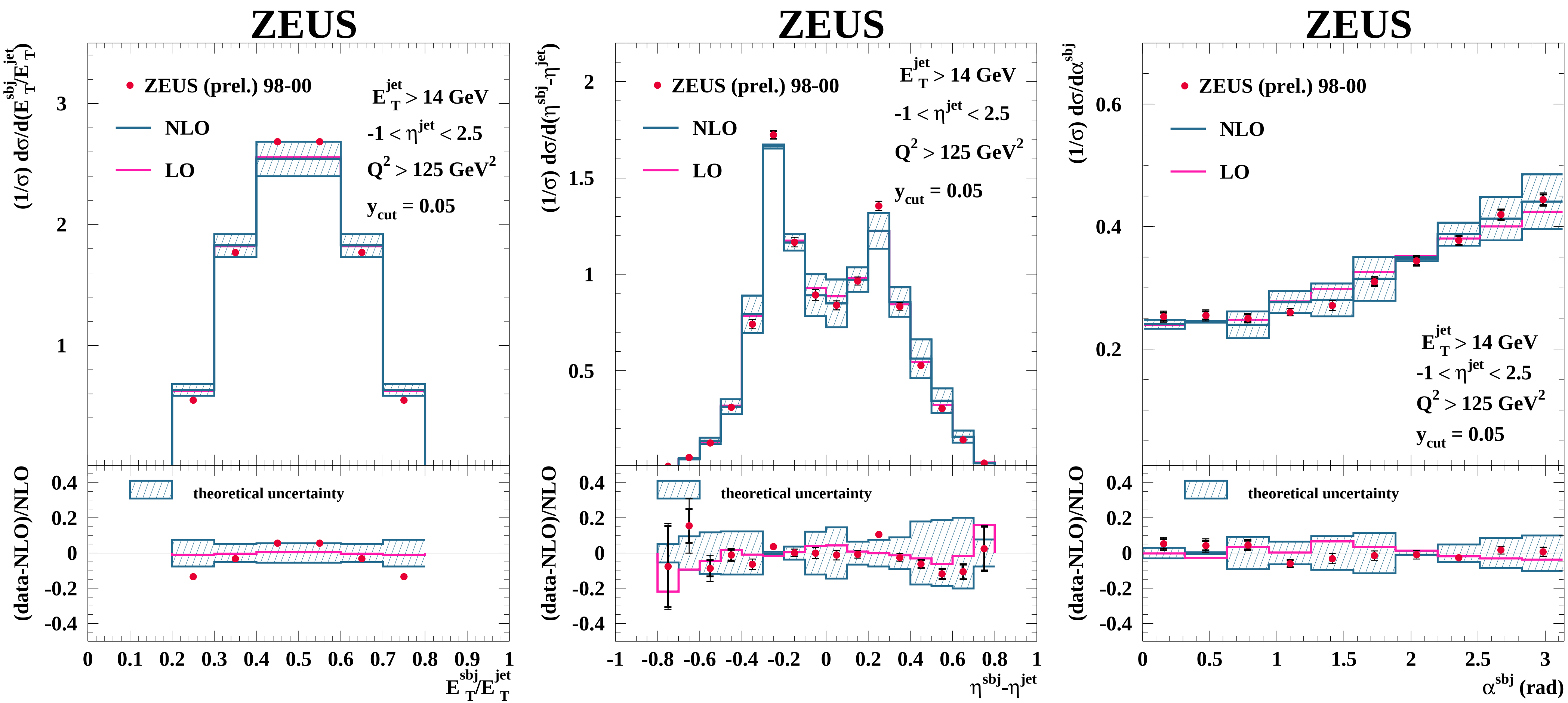
$\longrightarrow$ $\alpha_s(M_Z) = 0.1175$

$\longrightarrow$ renormalisation and factorisation scales, $\mu_R = \mu_F = Q$

$\longrightarrow$ corrected for hadronisation effects

Measurements of Subjet Distributions in NC DIS vs NLO

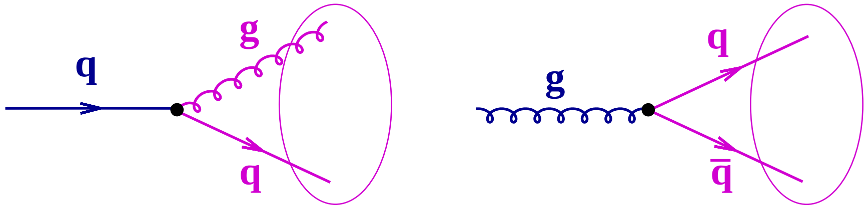
- **Measurements of the normalised cross sections for subjet production as functions of E_T^{sbj}/E_T^{jet}, $\eta^{sbj} - \eta^{jet}$ and α^{sbj} vs LO and NLO QCD calculations**

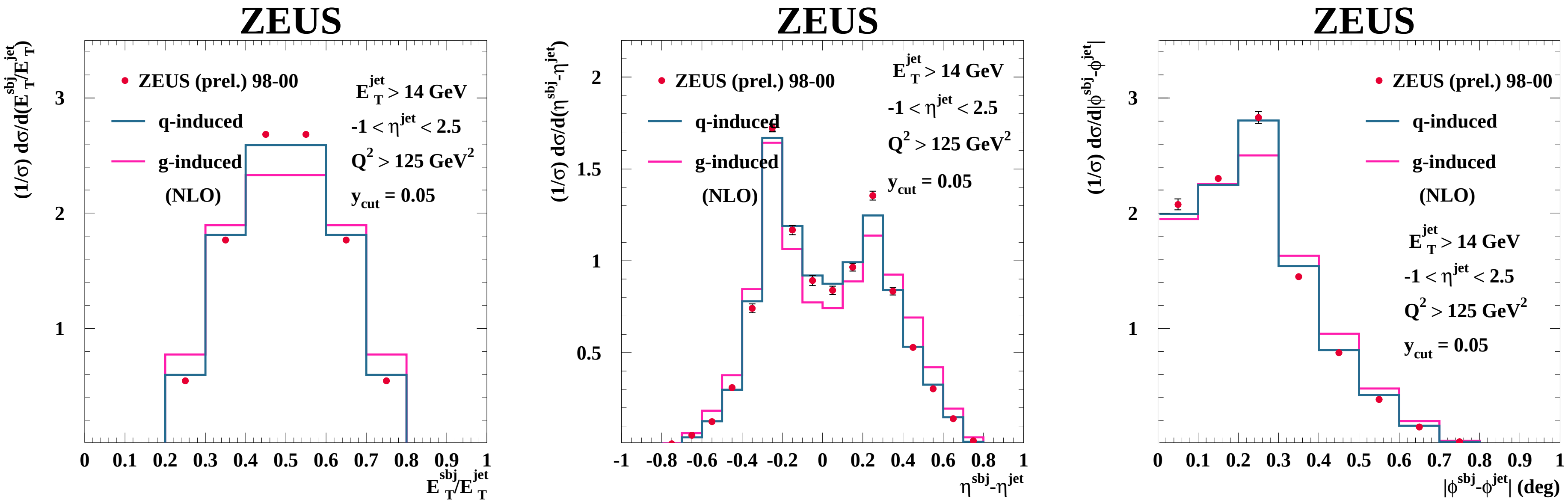


→ NLO QCD calculations describe the data within ±10%

Measurements of Subjet Distributions in NC DIS

- Measurements of the normalised cross sections for subjet production as functions of E_T^{sbj}/E_T^{jet}, $\eta^{sbj} - \eta^{jet}$ and $\phi^{sbj} - \phi^{jet}$ vs QCD calculations for quark- (82%) and gluon-induced (18%) contributions (NLO predictions)





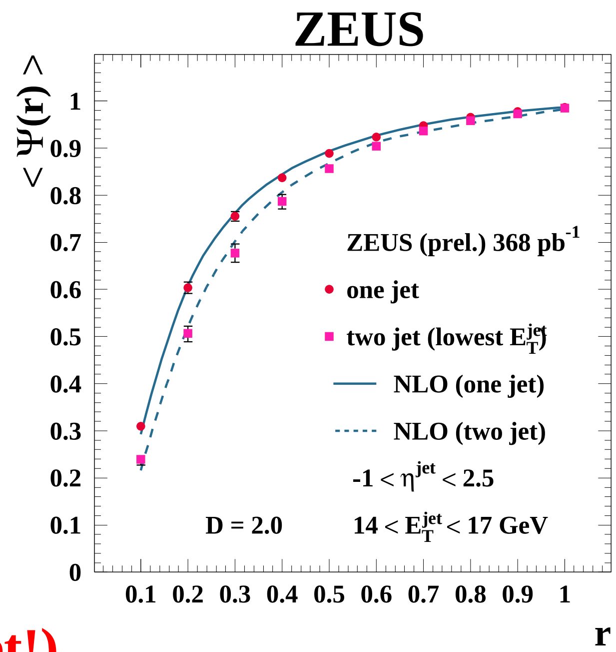
$\longrightarrow$ The data are well described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair

Summary

- Measurements of the **integrated jet shape** in NC DIS ($Q^2 > 125$ GeV^2) for jets with $E_T^{jet} > 14$ GeV using HERA II data ($\mathcal{L} = 368$ pb^{-1})

$\longrightarrow$ The jet with lowest E_T^{jet} in two-jet events is **broader** than that of a sample of one-jet events for the same range in E_T^{jet}

$\longrightarrow$ NLO QCD calculations **(with up to three partons in a jet!)** describe the data reasonably well



- Measurements of the normalised cross sections for **subjet production** in NC DIS ($Q^2 > 125$ GeV^2)

$\longrightarrow$ the **pattern of QCD radiation** as implemented in the NLO calculations reproduces the measured **subjet distributions**

$\longrightarrow$ the subjet distributions are well described by the calculations for jet arising from **the splitting of a quark into a quark-gluon pair**